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ORIGINAL PAPER

Soil nitrogen transformations varied with plant community under Nanchang urban forests in mid-subtropical zone of China

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Abstract: Soil N transformations using the polyvinyl chloride (PVC) closed-top tube in situ incubation method were studied in Nanchang urban forests of the mid-subtropical region of China in different months of 2007. Four plots of 20 m × 20 m were established in four different plant communities that represented typical successional stages of forest development including shrubs, coniferous forest, mixed forest and broad-leaved forest. Average concentrations of soil NH_4^+-N from January to December were not different among the four plant communities. The concentrations of soil NO_3^--N and mineral N, and the annual rates of ammonification, nitrification and net N-mineralization under the early successional shrub community and coniferous forest were generally lower than that of the late successional mixed and broad-leaved forests (p<0.05). Similar differences among the plant communities were also shown in the relative nitrification index (NH_4^+-N/NO_3^--N) and relative nitrification intensity (nitrification rate/net N-mineralization rate). The annual net N-mineralization rate was increased from younger to older plant communities, from 15.1 and 41.4 kg·ha^{-1}·a^{-1} under the shrubs and coniferous forest communities to 98.0 and 112.9 kg·ha^{-1}·a^{-1} under the mixed and broad-leaved forests, respectively. Moreover, the high annual nitrification rates (50–70 kg·ha^{-1}·a^{-1}) and its end product, NO_3^--N (2.4–3.8 mg·kg^{-1}), under older plant communities could increase the potential risk of N loss. Additionally, the temporal patterns of the different soil N variables mentioned above varied with different plant community due to the combined affects of natural biological processes associated with forest maturation and urbanization. Our results indicated that urban forests are moving towards a state of "N saturation" (extremely nitrification rate and NO_3^--N content) as they mature.

Keywords: global change; nitrogen saturation; soil nitrogen mineralization; Southern China; urban forests

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Introduction

During the last century, rapid urban growth has exerted strong pressure on land resources in urban and peri-urban areas (Hong et al. 2006). Now, more than half of the globe's population (3.3 billion people) is living in towns and cities, and the number and proportion of urban dwellers will continue to rise quickly. Urban population will grow to 4.9 billion by 2030 and especially in developing countries. The urban population of Africa and Asia is expected to double between 2000 and 2030 (UNFPA 2007). As an important component of urban landscapes, urban forests (shrubs and trees) can provide a variety of services, such as moderating temperatures and microclimates, stabilizing soils, reducing noise level, habitats for birds and other wildlife, and enhancing recreational functions (Zhu et al. 2008). Urban forests play a vital role in the environmental and aesthetic ''health'' of cities (Iverson et al. 2000; Atmis et al. 2007; Chen et al. 2010a).

Nitrogen (N) is one of the key determinants of plant biomass growth (Pastor et al. 1984). Net N mineralization, the transformation process of organic N into inorganic N, is an early determinant of soil N availability. The microbial mineralization of NH_4^+-N from soil organic matter is the principal source of plant available N in most forest ecosystems. The rates of N mineralization can regulate the productivity and stability of forests (Reich et al. 1997; Chen et al. 2006). At the same time, N can also be a pollutant (Tørseth et al. 1998). For example, excess nitrification generally results in water and soil pollution and greenhouse gas emissions (NO_2) (Davidson et al. 1993). Additionally, N deposition has become a serious problem with increasing N emissions to the atmosphere because human activity remains elevated in industrialized regions of the world and is accelerating in many developing regions (Galloway 1995; Fang et al. 2010). The po-

tential for N deposition leads to increases in N availability and nitrate mobility in soils over time, causing soil and stream acidification, and N imbalances in trees, and forest decline, which is called N saturation (Aber et al. 1998). Urban areas in most less-developed regions are experiencing rapid rates of population growth, industrialization and consequent elevated levels of N deposition (NO_3^--N and NH_4^+-N), greenhouse gases (CO_2, CH_4 and N_xO_y), pollutants (O_3 and SO_2), and temperature, which are driving environmental changes both regionally and globally (Pickett et al. 2001; Lorenz et al. 2009). However, the implication of these changes on terrestrial ecosystem N cycling has received limiting study in urban forests (Chen et al. 2010a).

Urban forestry has developed as an integrative, multidisciplinary approach to the planning and management of forest and plant resources ranging from street trees to peri-urban woodlands in and near urban areas (Konijnendijk 2003). During the past several decades, large areas of forests located near Nanchang city, southern China have been transformed into urban forests due to rapid urbanization and the expansion of urban areas (Chen et al. 2010b). These newly created urban forests provide an opportunity to better understand soil N mineralization processes in urban forests which have been exposed to elevated levels of N deposition, temperature and soil pollutants (Grimm et al. 2008). Zhu et al. (1999) found that urban and suburban oak stands had higher soil NO_3^--N concentrations and nitrification rates than rural oak stands along an urban-to-rural transect in the metropolitan New York City area. Chen et al. (2010a) reported that urbanization altered soil mineral N pools, microbial biomass N, mineralization rates, foliar N concentrations and N resorption proficiencies in *Pinus elliottii* plantations located along a short urban-rural gradient in Nanchang, P. R. China. However, few studies examined variations of N mineralization processes in soil among different plant communities in urban forest ecosystems. Additionally, several simulated N deposition experiments showed that different plant communities have various responses to increased N additions, and the response magnitude depends largely on the amount of N deposition, initial nutrient pools (Aber et al. 1995; Fang et al. 2009). In general, relatively little ecological information about urban areas and especially soils is available as studies on urban ecosystems have been traditionally neglected by ecologists and soil scientists (Grimm et al. 2008).

In this study, four plant communities in different stages of secondary succession were selected to quantify soil N transformations in Nanchang, P. R. China, which is typical of many urban areas in less-developed countries due to the recent rapid growth in population, industry and motor vehicle usage (Chen et al. 2010a). Our overall goal was to quantify the temporal patterns of soil N mineralization processes and N availability under four urban plant communities of the mid-subtropical region of P. R. China to better understand the comprehensive effects of urbanization on soil N processes. Our specific hypotheses was that soil N transformation rates and its availability would rapidly increase with forest maturity from shrubs and coniferous forests to mixed and broad-leaved forests. Additionally, we expect that older forests (broad-leaved and mixed forests) are closer to "N saturation" than younger forests (coniferous forest and shrubs) due to the combined effects of natural biological processes associated with forest maturity and elevated N deposition from urbanization (Lovett et al. 2000; Fang et al. 2010).

Material and methods

Study area

This study was conducted in Nanchang City (E 115°27′–116°35′, N 28°09′–29°11′), the capital of Jiangxi Province, in the mid-subtropical zone of P. R. China. Nanchang City, with an area of 7402 km^2 and a population of 4.8 million, experienced a rapid population increase from 2.4 million to 4 million between 1970 and 1996 (Chen et al. 2010a). The subtropical monsoon climate is wet and mild with a mean annual precipitation of about 1600–1800 mm, a mean annual relative humidity of 77%, and a mean annual temperature of 17.5ºC based on the climate data of the past 50 years (Yu 2009). The monthly variations in precipitation and air temperature in 2007 are shown in Fig. 1. The average useable sunlight is 1900 h·a^{-1}, and the frost free period is 291 d·a^{-1}. Urban areas tend to be warmer and drier than rural areas as the annual mean temperature in urban areas being 2–3ºC higher than that in rural areas, and relative humidity of urban areas being 2% lower in winter and 8% lower in summer than those in rural areas, respectively; the percentage of acid rain events in urban and suburban areas were 91.3% and 62.8%, with mean pH of 4.42 and 5.59, NH_4^+-N concentration of 1.01 and 0.47 mg·L^{-1}, and NO_3^--N concentration of 1.17 and 0.17 mg·L^{-1}, respectively (Yu 2009).

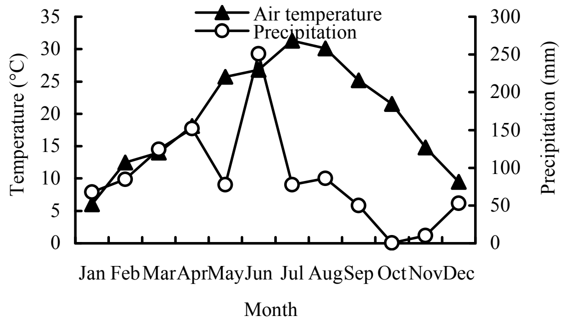

Fig. 1 Seasonal variations in air temperature and precipitation in 2007 (Data from Yu 2009)

Nanchang is considered as "Garden City" due to its high vegetation cover (38.2%) and average green area per person (7.5 m^2·person^{-1}) (Yu 2009). The study plots are located on the Nanchang University (NCU) campus, which is located in western Nanchang city with an area of 240 ha, and on the Jiangxi Agricultural University (JAU) campus, which is located in northern Nanchang city with an area of 1 000 ha. Both campuses were chosen as demonstration areas of ecological urban forest by the Nanchang government due to the diverse vegetation types and high vegetation cover (>50%) with some remnant secondary

forests. Four plots of 20 m × 20 m were established in four different plant communities that represented typical successional stages of forest development including shrubs, coniferous forest, mixed forest and broad-leaved forest (Table 1). Plots selected for the study are on well-drained flat sites. Shrub communities at NCU and JAU had often been cut down by local farmers for fuel before ten years. Other forest communities belong to secondary forests with human moderate disturbances, such as litter harvesting and walking. The soils at each site are Ultisols (or local name, red soil), which derived from Quaternary red clay that is a typical soil type in the mid-tropical zone of China. The soil of the area is formed from arenaceous shale and is approximately 1 m in depth (Chen et al. 2010b).

Table 1. Stand characteristics of eight plots under four different plant communities in Nanchang urban forests

Site symbol	Location	Successional stage	Age* (year-old)	Vegetation coverage	DBH (cm)	Height (m)	Height of litter layer (cm)	Reprehensive species
NS	Nanchang Univ.	Shrubs	10	0.80	3.5	3.0	1.5	*Symplocos paniculata*, *Dicranopteris dichotoma*, *Rosa laevigata, Gardenia jasminoides*, *Smilax china*
JS	Jiangxi Agriculture Univ.	Shrubs	10	1.00	4.0	4.0	2.0	*Quercus serrata* var. *brevipetiolata*, *Adinandra millettii*, *Lindera aggregate*, *Loropetalum chinense, Dicranopteris dichotoma*
NC	Nanchang Univ.	Coniferous forest	18	0.70	10.8	10.0	2.5	*Pinus massoniana, Gardenia jasminoides*, *Adinandra millettii*, *Symplocos* sp., *Ligustrum quihoui*
JC	Jiangxi Agriculture Univ.	Coniferous forest	25	0.75	12.6	12.0	1.5	*Pinus massoniana*, *Rhododendron simsii*, *Lindera aggregate*, *Loropetalum chinense*
NM	Nanchang Univ.	Mixed forest	35	0.90	13.8	12.0	4.0	*Cyclobalanopsis glauca, Castanopsis sclerophylla*, *Liquidambar formosana*, *Cunninghamia lanceolata*, *Pinus massoniana*
JM	Jiangxi Agriculture Univ.	Mixed forest	32	0.95	12.0	10.0	1.5	*Castanopsis sclerophylla, Liquidambar formosana*, *Schima superba*, *Pinus elliottii, Pinus massoniana*
NB	Nanchang Univ.	Broad-leaved forest	60	0.85	20.0	15.0	2.5	*Cinnamomum camphora*, *Castanopsis sclerophylla*, *Schima superba*, *Lindera aggregate*, *Symplocos* sp.
JB	Jiangxi Agriculture Univ.	Broad-leaved forest	50	0.80	18.0	16.0	3.0	*Cinnamomum camphora, Castanopsis sclerophylla*, *Ilex chinensis*, *Liquidambar formosana*, *Camellia oleifera*

Notes: *Ages for dominant trees are estimated based on their growth rings in each plot, while shrubs ages are provided by local farmers. The history as forest site for each plant community is more than the age of dominant shrubs or trees mentioned in the Table. All sites have not been as croplands before two hundred years. The stand characteristics were investigated in 2007 according to the traditional ecological field methods.

Methods

We investigated stand characteristics and soil properties in four different plant communities in the mid-subtropical zone of P. R. China. We established replicate plots in each of the four communities, shrubs, coniferous forest, mixed forest and broad-leaved forest at NCU and JAU. We measured the dynamics of soil available N, which is closely correlated with N supply and N loss (Chen et al. 2006), and soil mineralization rates using the polyvinyl chloride (PVC) closed-top tube in situ incubation method from January to December 2007. This method is considered one of the most efficient measures for estimating plant uptake and potential loss of inorganic N derived from mineralization (Pastor et al. 1984; Reich et al. 1997; Chen et al. 2010a).

At the start of the field incubation experiment, each plot was subdivided into four subplots of 10 m×10 m. Near the center of each subplot, the forest floor was carefully removed and two covered PVC tube with a diameter of 4.0 cm was sunk into the soil to a depth of 15 cm. Measurements of soil N variables were conducted for a full year with twelve field incubation cycles and each runs for a one month period. At the beginning of each cycle, pre-incubation soil was sampled near each tube to measure the initial concentrations of NH_4^+-N, NO_3^--N and mineral N (NH_4^+-N plus NO_3^--N), three of which were analyzed to examine the dynamics of available N (NH_4^+-N, NO_3^--N and mineral N).

A subsample of 25 g from the pre- or post-incubation soil sample was mixed with 100 mL of 2-mol·L^{-1} KCl, shaken for 0.5 h, and left to stand overnight at 4 °C. The NH_4^+-N and NO_3^--N in the supernatant were separately measured by spectrophotometry following filtration using the indophenol blue method and the cadmium reduction method (Liu et al. 1996), respectively. Soil (10 g) from each of the pre- or post-incubation soil sample was dried in an oven at 105 °C until a constant weight for determining soil moisture content. Ammonification and nitrification rates were indicated by the increase in NH_4^+-N and NO_3^--N, respectively, with net N-mineralization indicated by the increase in the total amount of NH_4^+-N and NO_3^--N in the incubation relative to their paired initial samples. All concentrations of NH_4^+-N, NO_3^--N and mineral N in this study were based on dry soil weight and expressed on a mg·g^{-1} basis.

Additionally, soil samples were collected within each subplot using a 5.0-cm- sampling cylinder to determine soil bulk density at each of the three depths for 0–5, 5–10, and 10–15 cm in August 2007. The soil bulk density (g·cm^{-3}) was determined based on the dry soil weight per unit volume of the soil core at each depth. The conversion of ammonification, nitrification and net N mineralization units from mg N·g^{-1} to g·N·ha^{-1} was based on soil bulk density at a depth of 15 cm in each plot.

To determine soil properties within the eight plots, we measured soil pH, organic carbon(C), total N, and total phosphorus (P) on pre-incubation soil samples. Soil pH was measured in a 1:2.5

mixture of soil and deionized water using a glass electrode. Soil organic C was determined by dichromate oxidation and titration with ferrous ammonium sulfate. Total N was determined by the microkjeldahl method and samples were analyzed for total P by a phosphomolybdic acid blue color method (Liu et al. 1996).

Statistical analysis

Differences in surface soil properties, including soil density, pH, organic C, total N, total P, C/N ratio, N/P ratio, were analyzed using one-way analysis of variance (ANOVA) with plot as the fixed main effect. Tukey's multiple comparisons method was used to identify significant differences among communities following significant ANOVA tests. A two-way repeated measure ANOVA was used to examine the effects of plant community and their interactions on soil NH_4^+-N, NO_3^--N, mineral N, ammonification, nitrification and net N-mineralization rates in the twelve one-month long incubations. Tukey's multiple comparisons were used to identify significant differences in annual and monthly values among plant communities.

The relationship between weather factors (air temperature and precipitation) and soil N availability (soil NH_4^+-N, NO_3^--N, mineral N, ammonification, nitrification and net N-mineralization rates) was determined using Spearman's correlation coefficient based on the average monthly values for each community type. The relationships between soil properties (e.g. soil bulk density, pH, organic C, total N, total P, C:N, N:P) and soil N availability were determined using bivariate correlation analysis with Spearman's correlation coefficient based on the average value of each plot. SPSS software (SPSS Inc. 2001, Version 11.0) was used to perform all analyses. All statistical tests were considered significant at $\alpha = 0.05$.

Results

Soil basic properties

Soil pH and bulk density showed no significant differences among the four plant communities. However, soil bulk density under similar plant communities (except shrubs) was much higher at NCU than at JAU (Table 2). Soil organic C, total N and total P concentrations generally increased with forest maturity. Soil C/N ratios were highest in the shrub community as compared to the other plant communities, and the soil N/P ratio was lowest in shrub and highest in mixed forest community (Table 2). Meanwhile, soil organic C under coniferous forests was higher at JAU than at NCU, soil total N and total P under broad-leaved forests were higher at NCU than at JAU (Table 2).

Table 2. Main surface (0-15 cm) soil properties of eight plots under four different plant communities in Nanchang urban forests

Plots	Bulk density ($g·cm^{-3}$)	pH	Organic carbon ($g·kg^{-1}$)	Total nitrogen ($g·kg^{-1}$)	Total phosphorus ($g·kg^{-1}$)	C/ N ratio	N/ P ratio
NS	1.49±0.02a	4.45±0.10ab	6.79±0.48c	0.25±0.02d	0.13±0.01d	27.85±1.48a	1.93±0.12cd
JS	1.11±0.04e	4.57±0.03ab	6.20±0.70c	0.24±0.03d	0.20±0.01cd	26.62±2,68a	1.26±0.23d
NC	1.34±0.04c	4.50±0.03ab	8.37±0.58c	0.58±0.02c	0.25±0.03bc	14.35±0.70b	2.43±0.20bc
JC	1.26±0.03c	4.64±0.06ab	12.27±0.44b	0.60±0.02c	0.28±0.01bc	20.58±0.82b	2.18±0.11bc
NM	1.33±0.01c	4.37±0.03b	14.19±0.49ab	0.92±0.06b	0.21±0.01cd	15.76±1.45bc	4.40±0.35a
JM	1.14±0.02e	4.75±0.04ab	14.90±0.79a	0.90±0.08b	0.23±0.02c	16.93±1.40b	4.06±0.49a
NB	1.40±0.02b	4.80±0.34ab	13.95±0.34ab	1.43±0.06a	0.57±0.04a	9.79±0.44c	2.54±0.07bc
JB	1.26±0.02d	5.14±0.14a	16.19±0.38a	1.01±0.06b	0.32±0.02b	16.17±0.85bc	3.14±0.12b

Notes: NS, NC, NM and NB represent shrub, coniferous, mixed and broad-leaved forest, respectively, at Nanchang University, while JS, JC, JM and JB represent the corresponding plant communities at Jiangxi Agricultural University, the same below. Values are mean ± 1 SE, *n*=4, the same letters in the same column indicate no significant differences, while different letters represent differences among eight plots ($p<0.05$).

Soil available N

The effects of plant community and months on soil NH_4^+-N, NO_3^--N and mineral N concentrations were statistically significant, with the exception that plant community had no significant effect on soil NH_4^+-N concentrations. There were not interactive effects of plant community and months on soil NH_4^+-N, NO_3^--N and mineral N concentrations (Table 3). The annual average concentration of soil NO_3^--N and mineral N increased with forest maturity at both NCU and JAU sites (Table 4). Soil NO_3^--N and mineral N concentrations under mixed forests were higher at JAU than at NCU, while they under broad-leaved forest showed opposite trend (Table 4). Additionally, the monthly dynamics of soil NH_4^+-N, NO_3^--N and mineral N concentrations showed complex temporal patterns for each plant community as well as when averaged over all plant communities (Fig. 2).

Soil N mineralization

The effects of plant community on soil ammonification, nitrification and net N-mineralization rates were significant. The effects of months and interactions with plant community on soil ammonification, nitrification and net-N mineralization rates were also significant except for the effect of months on soil ammonification (Table 3). The annual rates of ammonification, nitrification and net N-mineralization increased with forest maturity (Table 4). The ammonification rate in mixed forests was higher at NCU than at JAU, while the rates of nitrification and net N-

mineralization showed the opposite trend (Table 4). Additionally, the monthly dynamics of ammonification, ratio of nitrification to net N-mineralization showed complex temporal patterns for each plant community (Fig. 3).

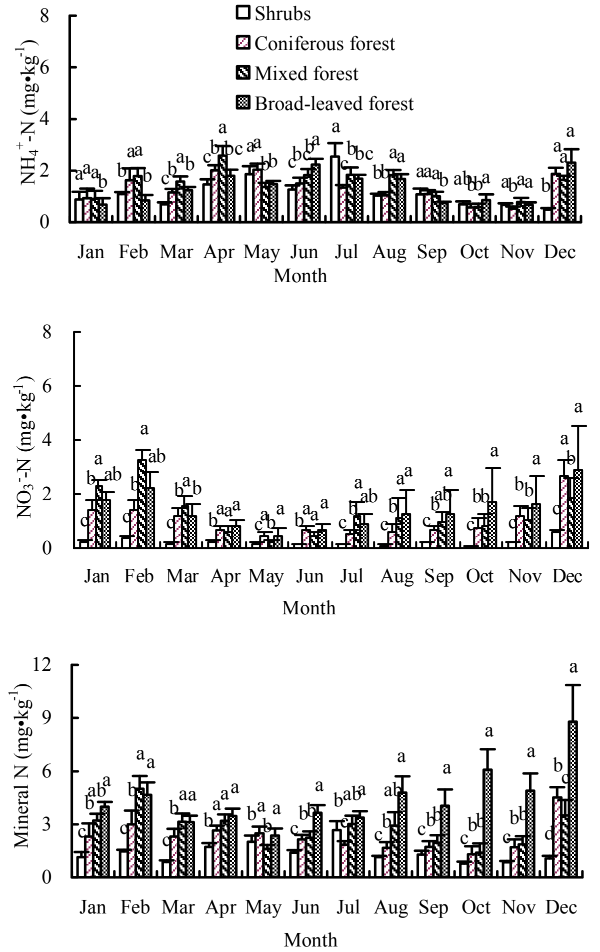

Fig. 2 The monthly variations of soil NH_4^+-N, NO_3^--N and mineral N concentrations under four different plant communities in Nanchang suburban forests. Bar indicates standard error of mean. Different letters indicate the significant difference of mean values (p<0.05) within each month among four plant communities.

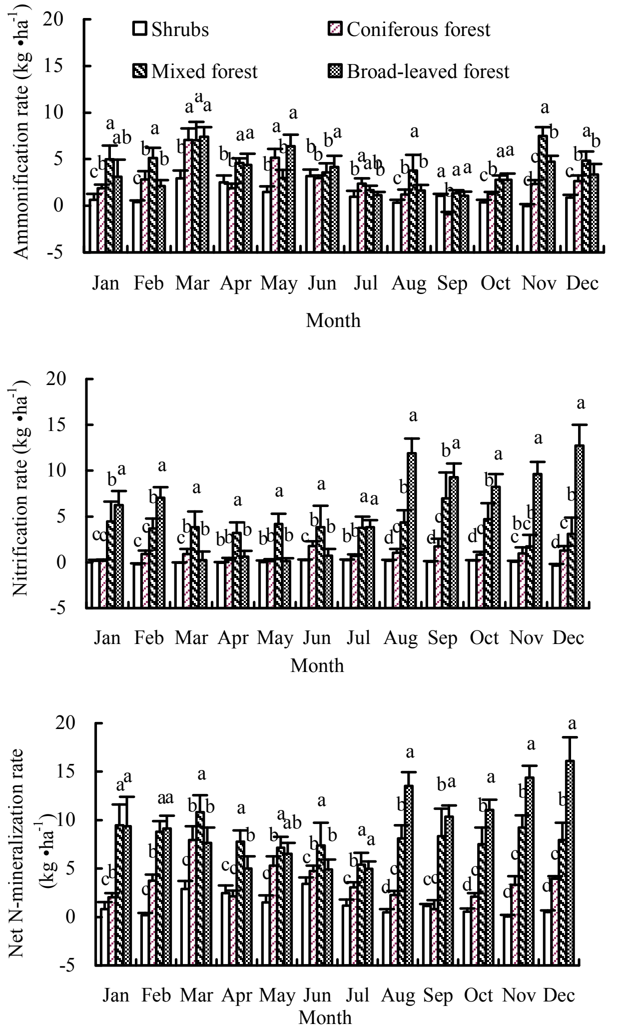

Fig. 3 The monthly variations of soil ammonification, nitrification and net N-mineralization rates at 30 days under four different plant communities in Nanchang suburban forests

Bar indicates standard error of mean. Different letters indicate the significant difference of mean values (p<0.05) within each month among four plant communities

Table 3. Effects of plant community and months on soil NH_4^+-N, NO_3^--N, mineral N concentrations (mg·kg^{-1}), ammonification, nitrification and net N-mineralization rates (kg·ha^{-1}·30d^{-1}) under four different plant communities in Nanchang urban forests

Factors	df	F Value					
		NH_4^+-N	NO_3^--N	Mineral N	Ammonification	Nitrification	Net N-mineralization
Plant community	3	1.18^{NS}	32.74***	24.41***	7.15***	20.83***	31.44***
Month	11	4.37***	3.65**	2.16*	2.91**	1.55^{NS}	0.83^{NS}
Plant community ×month	33	0.82^{NS}	1.22^{NS}	1.27^{NS}	0.56^{NS}	1.33^{NS}	0.97^{NS}

Notes: ^{NS} p>0.05, *p<0.05, **p<0.01, **** p<0.001.

Relationships among weather factors, soil properties and soil N availabilities

Soil NO_3^--N was negatively correlated with air temperature under each plant community. In contrast, air temperature was positively correlated with soil nitrification rate in the shrub community while it was negatively correlated with soil ammonification and net N-mineralization rates in the mixed forest. Precipitation was positively correlated with soil net N-mineralization rate under shrubs, while it was negatively correlated with soil net N-

mineralization rate under broad-leaved forest (Table 5).

As expected, both soil organic C and total N concentrations were positively correlated with most indices of soil N availability, except organic C vs ammonification rate and total N vs NH_4^+-N concentration (Table 6). Additionally, soil pH and total P were positively correlated with NO_3^--N, mineral N and nitrification. Soil C/N ratio was negatively correlated with ammonification and net N-mineralization rates, while N/P ratio was positively correlated with both N variables mentioned above (Table 6).

Table 4. Values of soil NH_4^+-N, NO_3^--N, mineral N concentrations, the relative nitrification index (ratio of NO_3^--N to mineral N), ammonification, nitrification and net N-mineralization rates, and the relative nitrification intensity (ratio of nitrification rate to net N-mineralization rate) of eight plots under four different plant communities in Nanchang urban forests

Plots	NH_4^+-N ($mg \cdot kg^{-1}$)	NO_3^--N ($mg \cdot kg^{-1}$)	Mineral N ($mg \cdot kg^{-1}$)	The relative nitrification index	Ammonification ($kg \cdot ha^{-1} \cdot 30d^{-1}$)	Nitrification ($kg \cdot ha^{-1} \cdot 30d^{-1}$)	Net N-mineralization ($kg \cdot ha^{-1} \cdot 30d^{-1}$)	The relative nitrification intensity
NS	1.10±0.10b	0.27±0.04d	1.37±0.10d	0.20±0.03de	1.32±0.25de	0.03±0.06b	1.35±0.25c	0.02±0.00c
JS	1.19±0.14ab	0.17±0.01d	1.36±0.13d	0.13±0.02e	1.13±0.26e	0.05±0.03b	1.18±0.27c	0.04±0.00c
NC	1.11±0.11b	0.54±0.09cd	1.65±0.17d	0.33±0.03cde	3.19±0.43bc	0.30±0.06b	3.49±0.45c	0.09±0.01c
JC	1.50±0.11ab	1.46±0.17bc	2.96±0.21bc	0.49±0.03bc	1.93±0.27cde	1.48±0.23b	3.41±0.32c	0.43±0.02ab
NM	1.33±0.14ab	0.76±0.14cd	2.09±0.19cd	0.36±0.04cd	5.49±0.52a	1.17±0.29b	6.66±0.72b	0.18±0.02bc
JM	1.62±0.09a	1.79±0.23b	3.41±0.27b	0.52±0.03bc	2.88±0.39bcd	6.80±0.57a	9.68±0.59a	0.70±0.03a
NB	1.24±0.15ab	3.79±0.46a	5.03±0.50a	0.75±0.04a	3.94±0.57ab	6.05±0.84a	9.99±0.84a	0.61±0.03a
JB	1.46±0.08ab	2.38±0.27b	3.84±0.29b	0.62±0.03ab	3.12±0.34bc	5.72±0.80a	8.84±0.77ab	0.65±0.03a

Notes: Values are mean ± 1 SE, n=48, four replications per plot for 12 months, the same letters in the same column indicate no significant differences, while different letters represent differences among eight plots (p<0.05).

Table 5. Spearman's correlation coefficients between weather factor and soil nitrogen availability for each plant communities in Nanchang urban forests (n=12)

Weather factor	Plant community type	NH_4^+-N	NO_3^--N	Mineral N	Ammonification	Nitrification	Net N-mineralization
Air temperature	Shrubs	0.61*	-0.77**	0.47^{NS}	0.16^{NS}	0.64*	0.30^{NS}
	Coniferous forest	0.06^{NS}	-0.91***	-0.52^{NS}	-0.16^{NS}	0.15^{NS}	-0.10^{NS}
	Mixed forest	0.39^{NS}	-0.60*	-0.57^{NS}	-0.71*	0.26^{NS}	-0.70*
	Broad-leaved forest	0.34^{NS}	-0.59*	-0.30^{NS}	-0.31^{NS}	-0.15^{NS}	-0.41^{NS}
Precipitation	Shrubs	0.50^{NS}	-0.04^{NS}	0.50^{NS}	0.62*	0.00^{NS}	0.59*
	Coniferous forest	0.51^{NS}	-0.22^{NS}	0.36^{NS}	0.40^{NS}	0.04^{NS}	0.42^{NS}
	Mixed forest	0.80*	-0.09^{NS}	0.39^{NS}	0.13^{NS}	-0.20^{NS}	-0.10^{NS}
	Broad-leaved forest	0.55^{NS}	-0.70*	-0.57^{NS}	0.23^{NS}	-0.54^{NS}	-0.69*

Notes: ^{NS} p>0.05, * p< 0.05, ** p < 0.01, *** p< 0.001

Table 6. Spearman's correlation coefficients between surface soil basic properties and soil nitrogen availability under four different plant communities in Nanchang urban forests (n=8)

Nitrogen availability	Bulk density	pH	Organic carbon	Total N	Total P	C: N	N: P
NH_4^+-N	-0.59^{NS}	0.53^{NS}	0.74*	0.50^{NS}	0.43^{NS}	-0.10^{NS}	0.57^{NS}
NO_3^--N	0.07^{NS}	0.76*	0.81*	0.83**	0.86**	-0.60^{NS}	0.62^{NS}
Mineral N	0.07^{NS}	0.76*	0.81*	0.93**	0.86**	-0.60^{NS}	0.62^{NS}
Ammonification	0.38^{NS}	0.00^{NS}	0.57^{NS}	0.76*	0.50^{NS}	-0.91**	0.79*
Nitrification	-0.25^{NS}	0.74*	0.81*	0.79*	0.72*	-0.50^{NS}	0.67^{NS}
Net N-mineralization	0.13^{NS}	0.57^{NS}	0.81*	0.91**	0.69^{NS}	-0.74*	0.79^{*}

Notes: ^{NS} p>0.05, * p< 0.05, ** p< 0.01, *** p < 0.001.

Discussion

Characteristics of N saturation in urban forests

The variability of soil NH_4^+-N concentrations between months was much smaller than that of soil NO_3^--N, mineral N, nitrification and net N-mineralization among the four plant communities (Figs. 2 and 3). Surprisingly, soil NH_4^+-N concentrations were not significantly different among the four plant communities (Table 3), showing minimal variation among the eight plots (Table 4). In acidic forest soils, nitrification is controlled mainly by competitions between plants and nitrifying microbes. Nitrification tends to occur only where the supply of NH_4^+-N is high relative to plant demand (Vitousek et al. 1982). Our results indicate that soil microbes would supply sufficient amounts of NH_4^+-

N to meet plant needs, and excess NH_4^+-N would be nitrified to NO_3^--N by nitrobacteria and other microbes (Chen et al. 2010a). In contrast, soil NO_3^--N, nitrification rate, the relative nitrification index (ratio of NO_3^--N to mineral N) and relative nitrification intensity (ratio of nitrification rate to net N-mineralization rate) generally increased with forest maturity (Table 4). It is indicated that nitrification and its end product (NO_3^--N) become more dominant in mature forests as compared to younger forests.

Nitrification is an important process that results in ecosystem losses of N and other nutrients such as Ca, Mg and K (Likens et al. 1969). In European forests, nitrification occurred in stands receiving high atmospheric N inputs (>25 kg·ha^{-1}·a^{-1}) (Gundersen et al. 2006). In southern China, Fang et al. (2010) found that compared with rural forests, N variables, including N deposition of bulk and throughfall, soil nitrification rate and its end product (NO_3^--N), NO_3^--N leaching to stream were enhanced in urban and suburban forests. Prolonged elevated N deposition in forest ecosystems may eventually cause N saturation, which can result in NO_3^--N leaching and an imbalance in plant nutrient supplies and uptake (Aber et al. 1995). Thus, Fang et al. (2010) suggested that the urban and suburban forests would be N saturation status based on the conceptual model of N saturation (Aber et al. 1998). Chen et al. (2010) used slash pine (*Pinus elliottii*) forests located along a short urban-rural gradient in Nanchang, P. R. China to study N cycling responses to urbanization, and also found that soil nitrification rate and NO_3^--N concentration were enhanced in urban and suburban forests, which indicated that forests in suburban and urban areas are moving rapidly towards a state of N saturation. Compared with the published results, all soil nitrification rates in coniferous, mixed and broadleaved forests (11, 48, and 71 kg·ha^{-1}·a^{-1}) in this study were higher than those in rural slash pine forests (8 kg·ha^{-1}·a^{-1}), and lower than those in urban slash pine forests (114 kg·ha^{-1}·a^{-1}), (Chen et al. 2010a). Therefore, we suggest that older forests (at least for JM, NB and JB) in urban areas would be moving towards a state of N saturation due to the coupled effects of natural biological processes and environmental alteration from urbanization.

Additionally, our data indicated that relations of ecological factor and soil N availability (Table 5) varied depending on plant community. However, soil NO_3^--N concentrations usually were higher during the dormant season than during the growing season (Fig. 2). This can also be tested by negative correlations between soil NO_3^--N concentrations and air temperature under each plant community (Table 5). Consequently, higher concentrations of soil NO_3^--N in dormant season may easily result in potential environment problems, including N losses, water pollution and greenhouse gas emissions (Likens et al. 1969; Davidson et al. 1993). Therefore, we suggest that the seasonal inconsistency between soil NO_3^--N supply and plant N demand would be a symptom in urban forest to "N saturation" and a response to environmental pressures, especially N deposition.

Site history, physical disturbances, soil properties and N cycling

The increasing tendency for soil N transformation rates and N availability with forest maturity was observed at both the NCU and JAU sites (Table 4), which was also shown in soil organic C, total N and total P (Table 2). However, the relative nitrification index and intensity in each forest community (coniferous, mixed and broad-leaved forests, separately) were much lower at NCU than JAU site (Table 4). Due to the fact that there were similar dominant species in these forest communities at both research sites (Table 1), site differences, such as density of residents on the campus and the age of the campus (NCU is a new campus having been established five years ago with 40 thousand students whereas JAU has a 50-year history with approximately 15 thousand residents) may play an important mechanistic role in soil N dynamics (Iverson et al. 2000). Additionally, the intensity of direct disturbance by humans, such as litter raking, would be a reasonable factor to explain the significant variations in the components of soil availability between the NM and JM plots because of a thicker litter layer in NM than in JM (Table 1). Thus, site history and direct physical disturbances could be important factors impacting forest N cycling dynamics in urban areas (McDonnell et al. 1997; Lorenz et al. 2009).

As noted, our data also indicated that relations among different soil properties and various indices of N availability (Table 6) may be separately regulated (Kristensen et al. 1998). The effects of these urban environmental factors on soil N cycling can vary substantially from site to site because N transformation rates generally depend on soil properties, plant communities, climatic factors and human disturbances (Lorenz et al. 2009).

In conclusion, the temporal patterns of soil N mineralization processes and N availability in Nanchang urban forests varied depending on plant communities. The direct (e.g., forest development, site history, physical disturbances, litter raking) and indirect factors (such as elevated N deposition, CO_2 concentrations, O_3 concentrations, temperature) affected soil N pools and their transformations in urban forests. However, the annual rates of nitrification and net N-mineralization, and their end products (NO_3^--N and mineral N) generally increased with forest maturity from shrubs and coniferous forests to mixed and broad-leaved forests at both NCU and JAU sites. Similar differences among the plant communities were also shown in the relative nitrification index and intensity. We suggest that the older forests (broad-leaved and mixed forests) were closer to "N saturation" than younger forests (coniferous forest and shrubs) due to the combined effects of forest maturity and elevated N deposition from urbanization (Lovett et al. 2000; Fang et al. 2010). To further understand the effects of urbanization on soil N transformations, the influences of varied environmental conditions on forest soil N cycling in urban ecosystems must be studied.

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